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Developing a portable NRL fast frame rate seeing monitor

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Abstract

We describe the development of a portable NRL seeing monitor which consists of a 12 inch Meade f/10 telescope with a Dalsa Cad6 260x260 camera having 10 micron pixels. This seeing monitor is capable of up to 700 frames per second. We have three different techniques to measure Fried's r0 parameter: full aperture, two-hole mask, and two-hole mask with in-line intensifier. For the observations done at the Anderson Mesa, Arizona site in January-July 2004, we present comparison of Fried's r0 obtained. Calibration, observing techniques, and data analysis techniques are described. Comparison of the three different techniques is discussed.

Key words: seeing monitor, DIMM, fast rate camera

1.0 Introduction

The Navy's work in improving measurement of the positions of stars not only aid in guidance and navigation of ships and missiles, it has also allowed Navy to be one of the forefront runner in the field of astronomy for centuries. The Navy Prototype Optical Interferometer can accurately measure star position to within 1 mili-arcsec (mas). One of the major limitations of this measurement is the effect of the atmosphere. Although big interferometers are capable of measuring precise star positions, turbulent atmosphere "blurs" the image which causes inaccurate measurement of the star position. Various well established theories and experiments show that inhomogeneous spots in the atmosphere degrade the clear "seeing" of the stars which appear at the focal plane of the telescope. The more inhomogeneous the atmosphere, the more distortion we expect on the image (hence that's why stars twinkle). We describe building of a seeing monitor which incorporates high-speed camera coupled with Meade's 12 inch telescope with parallel optical window mask.

2.0 Differential Image Motion Seeing Monitor (DIMM)

Over the past few decades, the DIMM seeing monitor has been the "standard" for measuring seeing at a particular site [1]. Two simple and relatively easy-to-build systems arise out from this field. One uses differential image technique by using two-hole mask on telescope (with or without wedges); separated image of the same star's relative motion can yields Fried's r0. Another approach, called the full aperture method, is to obtain r0 is by calculating the average FWHM of a single star image. Both of them have advantages and disadvantages.

For the two-hole mask method, the mask acts as a filter to subtract relative telescope tracking and motion errors. The variance in the position of the apparent two stars allows us to ascertain the Fried's parameter r0 [2].

$$\sigma_l^2 = 2\lambda^2 r_0^{-5/3}\left[0.179D^{-1/3} - 0.0968d^{-1/3}\right] (1)$$

$$\sigma_t^2 = 2\lambda^2 r_0^{-5/3}\left[0.179D^{-1/3} - 0.145d^{-1/3}\right] (2)$$

where D is the aperture size, and d is the sub-aperture size. The system is relatively easy to build and is used by many sites for measurement. However, this has one drawback; the masking of the telescope decreases the amount of photons received. An ordinary inexpensive CCD camera cannot take measurements at higher frame rates (>100). Although the atmosphere's time constant is assumed to be in the order or tens of milliseconds, this can be affected by location and site characteristics. Thus there is a

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14. ABSTRACT
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need for systems capable of imaging at higher frame rates. For the DIMM method, adding a relatively cheap in-line intensifier can be useful, but care must be taken to avoid negative effects such as temporal smearing due to the persistence of the phosphors in the intensifier.

For full aperture methods, one star is observed at a fast frame rate to resolve speckles. These speckle are the product of atmospheric turbulences in the atmosphere. Since Fried's parameters are dictated by the limits of seeing [2],

$$r_0 = 0.98\frac{f \cdot \lambda}{FWHM} \quad (3)$$

one can obtain such information just by taking fast exposures of a single star. However, one major drawback is that relative telescope tracking and motion adds errors. For portable seeing systems where tripod and ground is relatively unstable, any instrument motion adds bias to the results. Various post processing algorithms can filter out the bias and the technique is robust and has been working well at varies site for seeing measurements [references].

One of the additional features in our system is addition of an in-line image intensifier to the two-hole mask method. The intensifier amplifies the faint signal allowing high frame rate data acquisition. Hence we can observe dimmer stars without being photon starved.

2.0 **Instrument and Site**

Our instrument is similar to many known seeing monitors [3]. The detector is a Dalsa Cad6 fast frame camera (a 260x260 array with 10 μm pixels). The camera does not need thermo cooling. The camera is configured with Matrox DigII framegrabber card which can take up to 700 frames per second (although the camera can take up to 955 frames per second we are currently limited by the bus speed of the computer). The program to control the camera is a hybrid of C++ and MATLAB drivers and programs.

The telescope is a Meade 12 inch Schmidt-Cassagrain. For the mask we punched two 3-inch holes separated 9 inches (center to center) apart in horizontal axis. The telescope is on an alt & az platform and uses two star alignment and tracking method built in by the Meade system. The computer is a 1.4GHz Pentium processor running Windows XP.

2.1 Calibration of Image Intensifier

As mentioned previously, we added an in line image intensifier for the two star method to boost the signal. First, we verified the performance of image intensifier. We did this by performing the following calibration on the ITT ultra-blue Gen 3 in-line image intensifier we obtained.

The set up is shown in figures 1.1 and 1.2. The intensifier is followed by two f/2 camera lenses as shown. The two lenses refocus the intensifier image onto the CCD. The f-numbers are set to yield a 1:1 image when coupled to the Dalsa CA-D6-0256W using two Nikkor F/1.2 lenses, each set to F/2. F/2 was a good compromise between efficient energy coupling and resolution. We note that using a lower F# resulted in significantly more gain, but at the further expense of resolution. Using a higher F# did not significantly improve resolution, as the resolution is limited by the micro-channel plate and P42 phosphor.

Figure 1.1

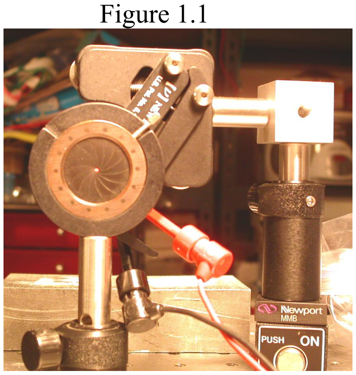


Figure 1.2

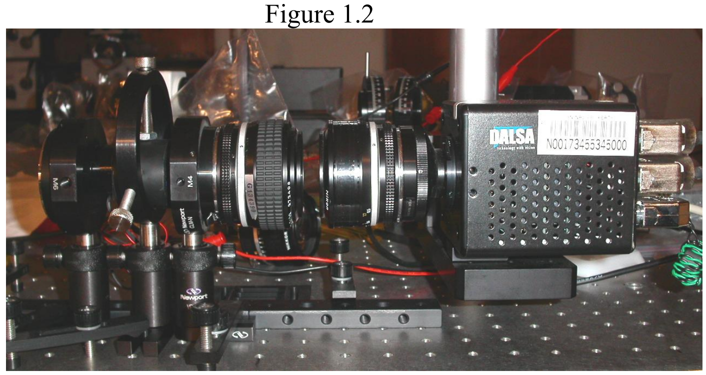


Figure 1.2 shows intensifier with two Nikkor lenses for re-imaging onto the CCD. The both lenses are set to f/2. The ~0.7mm variable intensity 670nm source was placed 1 meter away from the input imaging lens for this calibration work.

3.0 Calibration Result

Results shown in figures (2.1 – 2.6) are obtained by performing the following: Frame rates of 10, 20, 50, 100, 200, and 500Hz were selected for study with maximum gain on the intensifier. While viewing the peak intensity of the incoming image data, the LED power level was adjusted until a reading of 50 counts was reached. We used a Newport Power Meter to measure the total power emitted from the LED through the iris. Another set of data was collected without the image intensifier. The image intensifier gain was calculated as the ratio of the power required to achieve 50 counts without the intensifier vs. with the intensifier.

Figure 2.1 (10 Hz)

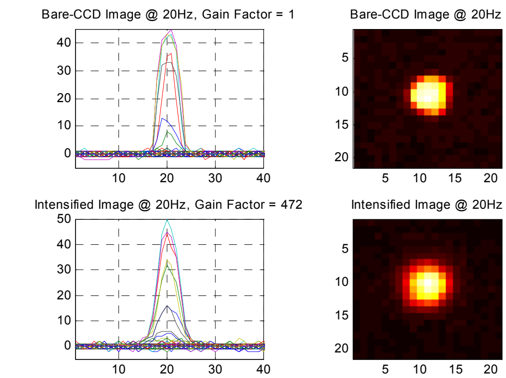


Figure 2.2 (20 Hz)

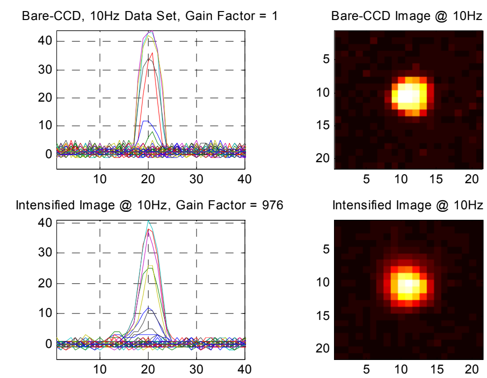


Figure 2.3 (50Hz)

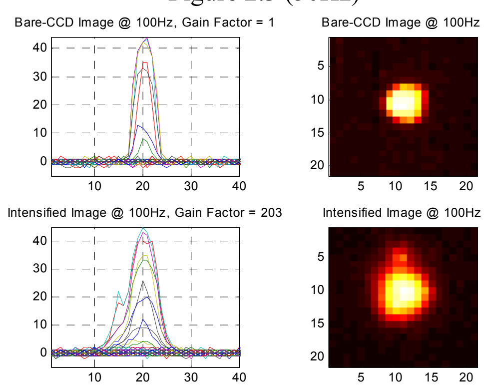


Figure 2.4 (100 Hz)

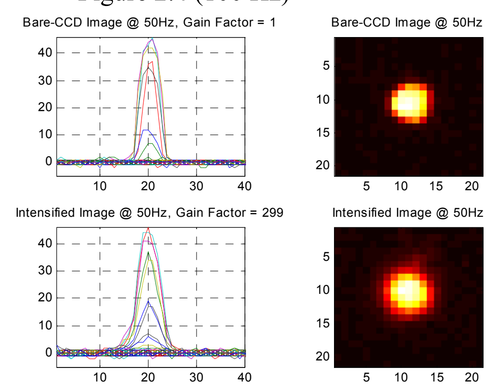


Figure 2.5 (200 Hz)

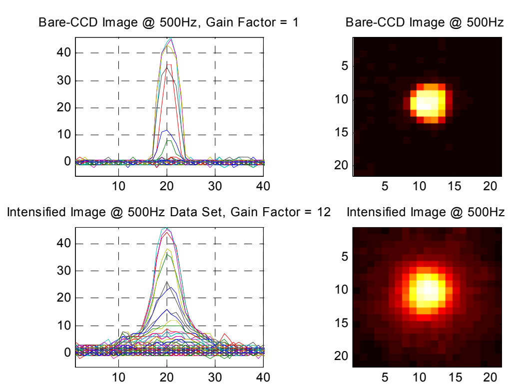
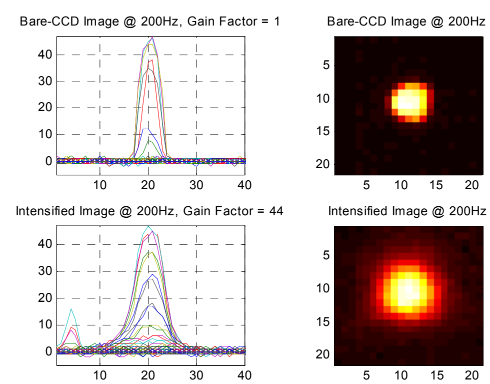


Figure 2.6 (500 Hz)



The gain varies from roughly 1000X to 10X as the frame rate is varied from 10Hz to 500Hz while maintaining a useable 50 counts signal level. The gain is nearly 2X the above for fast scanning input optical signals, most likely due to local capacitive charge depletion on the microchannel plate. The

resolution of the intensified Dalsa CA-D6 with 1:1 optical coupling at F/2 is degraded to 2 pixels minimum spot size (20um). However, we conclude that intensified images thresholded at the 50% level will have the same size as without the image intensifier. Although higher frame rates lead to more broadening/distortion of the resulting image, image intensifiers of this type should work well for small featured, mostly dark fields such as star images. Extended objects appear "washed-out" due to overlapping halo effects.

4.0 Observing Sites

All observations were performed in the Flagstaff, AZ vicinity at 3 different sites

- –NPOI site – January 8-9, 2004
- –Happy Jack Mountain – March 25-27, 2004
- –Naval Observatory Flagstaff Station (NOFS) – July 19-22, 2004

Previous measurements made at the NPOI site report an average of ~9cm seeing conditions throughout the year [4-6].

5.0 Seeing Measurements

Two separate systems are shown below. Figure 3.1 shows the image intensifier set up. Figure 3.2 shows the full aperture set up (w/o the intensifier). Focus on telescope was adjusted for least pixels for a star for each method. Figure 3.3 shows the instrumented mounted onto the Meade telescope.

Figure 3.1

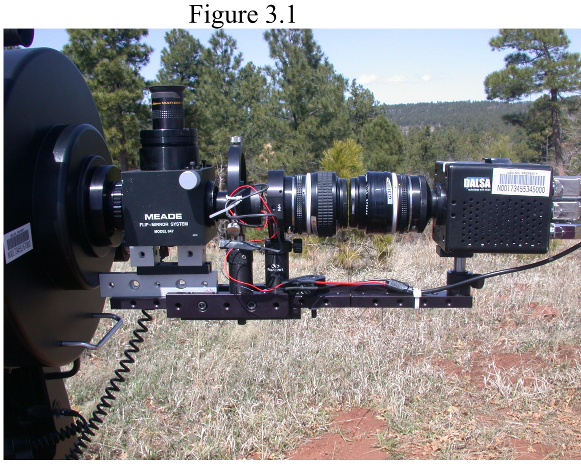


Figure 3.2

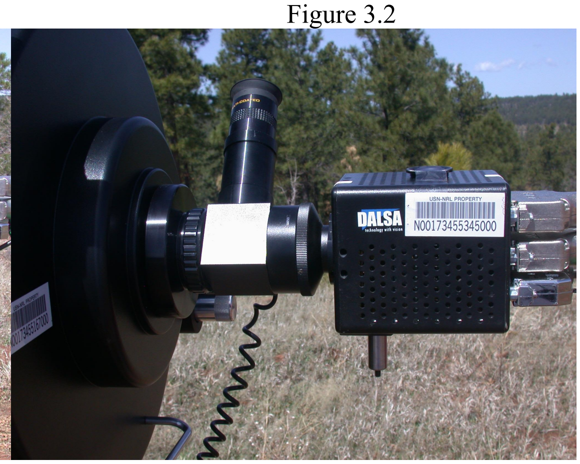


Figure 3.3

6.0 Observing technique

We set up and leveled the telescope at the observing site. Using a 9mm eyepiece with an illuminated reticle we performed the standard two star alignment. We usually chose a pair of stars with

greater than about 120 degrees separation such as combination of Deneb and Sirius, or Alkaid and Rigel. We repeated the alignment several time so that star stayed in the center circle of the eyepiece for more than ~20 minutes. This is good opportunity to align the finder scope so that if we had to move to a different star, we use it to align, not the main scope. Also a counter weight was used to balance the telescope since the CCD assembly was quite heavy.

6.1 Full aperture technique

Once computer and CCD is set up we placed the two hole mask in front and focused until two separate stars come together (this ensures focus). We the removed the mask off and recorder full aperture at different frame rates.

6.2 Two hole defocus method (intensifier & no intensifier)

Once the mask with two holes is in placed in front of the telescope, we separate the star image at least ¼ the length of the CCD to ensure total separation beyond the diffraction limit. Then we adjusted frame rate to ensure at least 2:1 s/n ratio and started taking data. When using the intensifier, we increased the frame rate to the maximum allowed by the system.

6.3 Two hole wedge method (intensifier & no intensifier)

The procedure is same as before with the addition of two 2” identical wedges with a 30 arcsecond deviation over the sub-apertures in the DIMM mask. The wedges were oriented to separate the stellar images by about the ¼ of the length of the CCD.

6.4 Dark

We covered the telescope aperture and recorded dark sample data at different frame rates.

7.0 Data Analysis

Each of the experimental configurations, two hole mask and full aperture, required a unique data reduction algorithm to produce comparable results. Both algorithms were implemented in MATLAB and operated offline on previously recorded data.

7.1 Two Hole DIMM Data Analysis

The algorithm used to determine r0 from the two holed DIMM data takes advantage of MATLAB’s Image Processing Toolbox to speed the data reduction process. This collection of functions allows us to identify the two stellar images, and compute the centroids of the two image spots quickly and accurately. The increase in speed gained from the new algorithm compared with a previous version that did not take advantage of toolbox functions is significant, around 75%, from approximately 30 minutes to analyze a complete data set to less than 8.

Figure 4.1 (Focused)

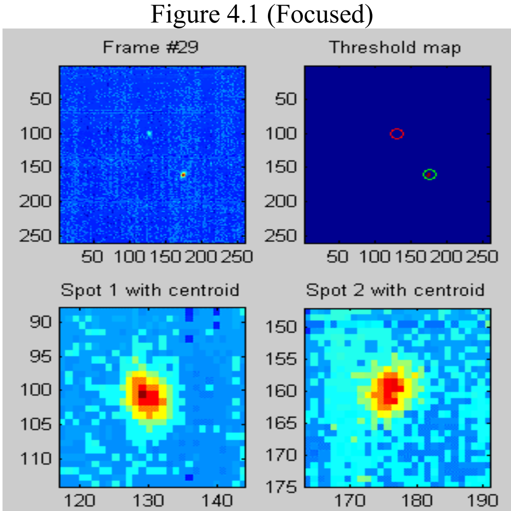
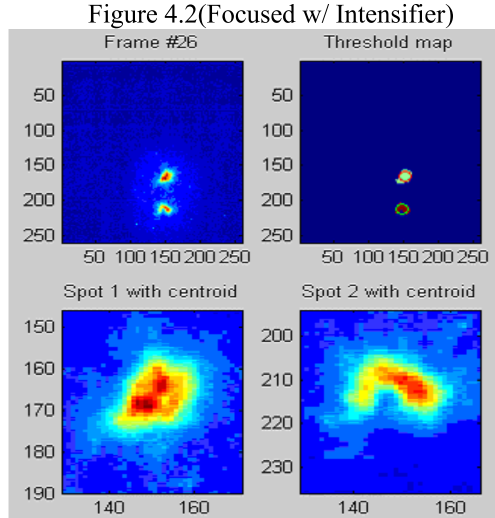


Figure 4.2(Focused w/ Intensifier)



The first step in the data analysis is to compensate for variations in the dark response of the camera. This is easily accomplished by subtracting a frame captured with the telescope aperture covered from the data frame. As shown in figure 4.1 above, the reduction in noise is significant in the raw image on upper left.

Next, the image data is thresholded at 30% of the peak pixel value in the frame. This further reduces the noise present as shown in Figure 4.1 upper right. The resulting image then undergoes a final noise reduction step in which all spots consisting of fewer than 10 pixels are discarded. As a result of this final step, the image contains only the two stellar images. In practice, this step is rarely necessary, since the preceding steps are usually sufficient to eliminate all image artifacts.

Once the dark compensation and thresholding operations are complete the image data is then processed using several MATLAB image-processing routines to find and compute the positions of the image centroids. The centroids positions are computed in pixels and the difference between the two centroids is calculated and stored in an array. Once all of the image frames have been processed, the array contains the differential centroid position information for the entire data set (usually 10,000 frames). In order to compute r0 we first convert the differential separation from pixels to arcseconds using the plate scale for the system that was calculated to be 0.66 arcsec/pixel. To compute r0, the standard deviation of this differential angular position is determined and the result used along with equation (1).

7.2 Full Aperture Data Analysis

The algorithm for determining r0 from the full aperture data is much simpler in principle than the two hole algorithm. In this case, we simply find the full width half maximum (FWHM) diameter of the stellar image in each frame and convert this to the corresponding value for seeing in arcseconds. r0 is easily computed from this value. In this work, we again took advantage of MATLAB's powerful image processing tools. As before, we subtract a representative dark image from each frame and then apply a threshold. In this case, the threshold is set at 50% of the peak pixel value in the image. We then find the area of the largest spot in the image, which is assumed to be the stellar image of interest, and determine the

Figure 5.1

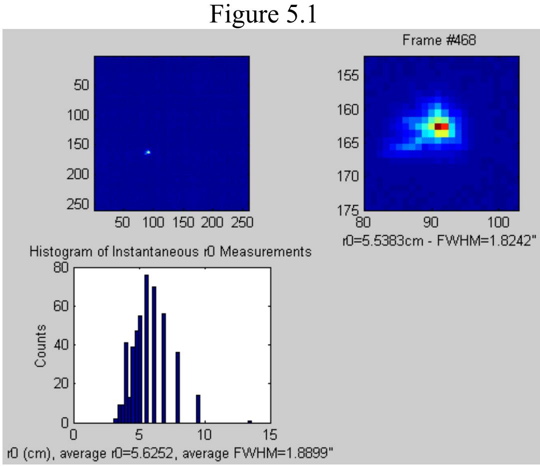
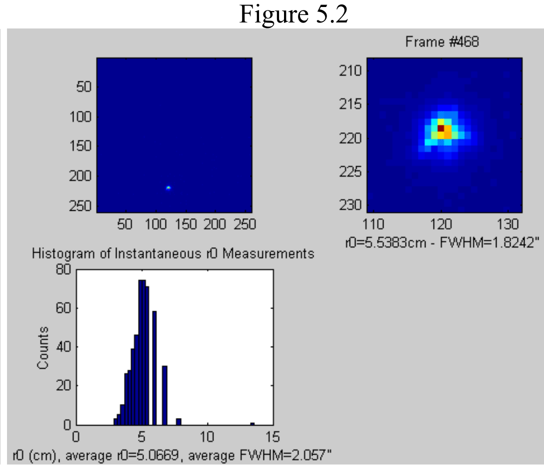


Figure 5.2



diameter of a circle with the same area as the spot. Seeing in arcseconds is easily found from this diameter by equation (2).

Figures 5.1 and 5.2 show typical result of a full aperture analysis. The upper left is the dark subtracted CCD image. The upper right shows the zoomed image of the star. The lower right is the histogram of the r0 calculation with corresponding r0 values printed below. For full aperture method focus becomes the most important issue in calculating the correct r0.

8.0 Results

Here we include plot of the results obtained at different sites:

Navy Prototype Optical Interferometer Result

Figure 6.1

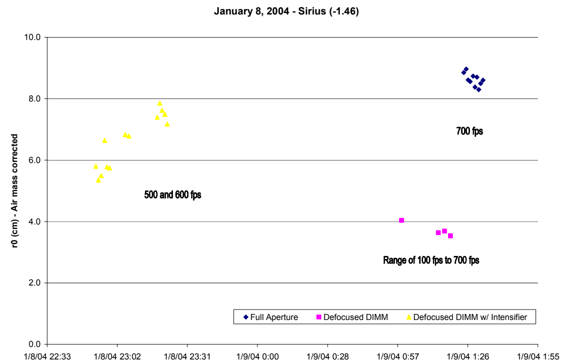
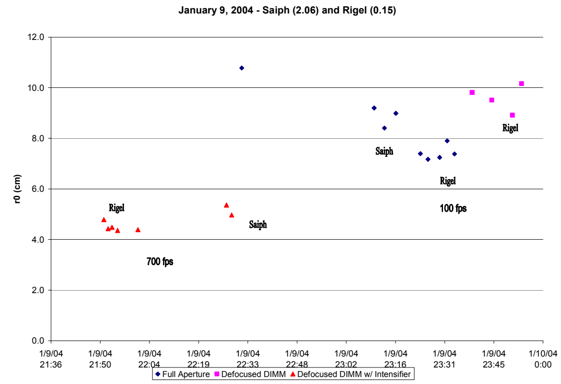


Figure 6.2



Happy Jack Mountain Result

Figure 6.3

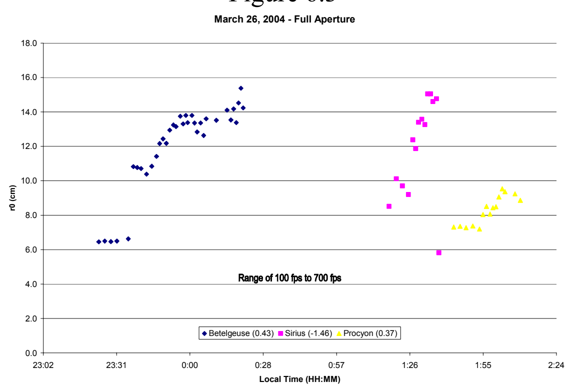


Figure 6.4

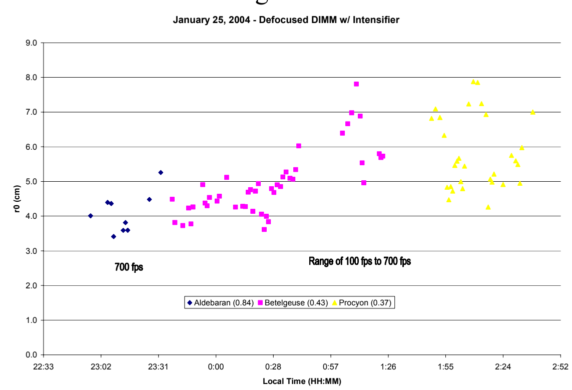
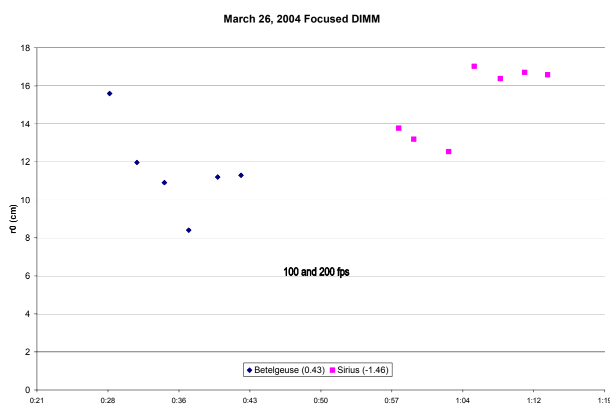


Figure 6.5



Naval Observatory Flagstaff Station Result

Figure 6.6

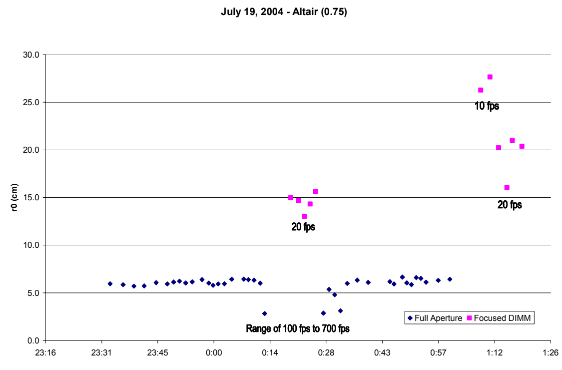
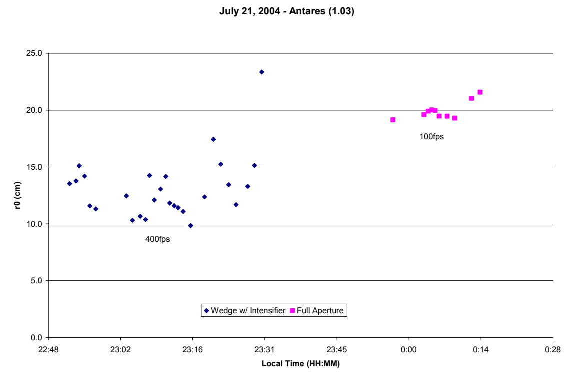


Figure 6.7



8.1 r0 versus frame rate

As shown in figures 6.1 to 6.7, we have collected data with stars of various magnitudes with different frame rates and different combination of methods to compare and contrast some of the strengths and weaknesses of each method. As one can see, the value of r0 computed from a given data set is strongly dependent on the frame rate. We find that for DIMM methods lower frame rates tend to overestimate r0 due to averaging of the image motion as shown in figure 7.1. As we take data at lower frame rates, the integration of the star image makes the image more stable, thus relative motion decreases. We see this effect starting below 300 frames/sec. For the full aperture method, lower frame rates tend to underestimate r0 due to blurring of the stellar image as shown in figure 7.2. As single star image broadens, the FWHM of the images increases. This automatically yields lower r0 than its actual seeing. We find that at least 300 frame/sec is needed to really obtain an accurate measure for r0. For results shown in figure 7.1 and 7.2 we compared observations under similar conditions at different frame rates for the different methods we examined

Figure 7.1 DIMM Method

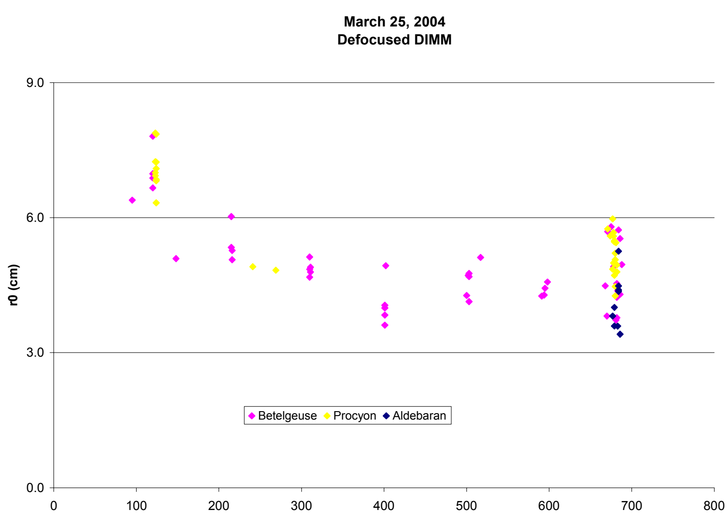
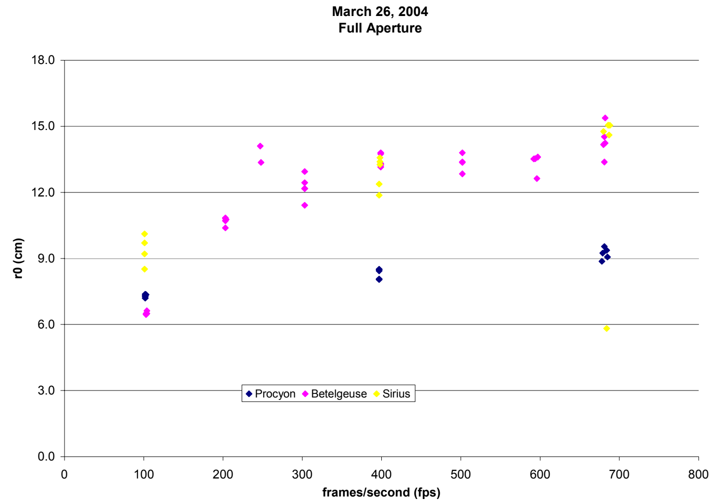


Figure 7.2 Full Aperture Method



For the intensifier method, we find that the maximum rate at which we can observe is at about 400 frames/sec. Previous data taken at 700 frames/sec did not work properly as the images showed effects of the slow time constant decay of the phosphor onto the CCD. Therefore the upper frame rate of the system is set by the time constant of the intensifier.

As for the average seeing conditions for the each site, we find, after discarding the data with upper and lower limits of the frame rate, in the table of summary below. We emphasize that the goal of this project was not to ascertain the correct r0 at different sites, it was to compare and contrast the different techniques and set guidelines as to which technique works best and why. Hence the result presented below are preliminary; more data is needed to justify and corroborate the result.

Table1

Site	Seeing
NPOI	8.5 cm
Happy Jack	10.5 cm
NOFS	7.1 cm

9.0 Conclusion

Five different methods of measuring r0 have been presented and tested.

9.1 DIMM Method

Specifically, focused DIMM methods yields good results, but limited in frame rate due to low light levels. If taking data below 300 frames/sec, the results seem to be biased towards better seeing condition than it actually is. One way to avoid this is to use brighter stars. However, choice of stars is limited at a given night. For example the, fastest rate with current CCD observing the brightest star in the sky (i.e Sirius) is about 100 frames/sec.

To remedy the faint signal problem, focused DIMM with Image Intensifier is recommended. This method offers good results for dimmer stars but bright stars result in smearing artifacts which cause r0 to be underestimated. Also another drawback is that the measurement is limited to less than 400 frames per second due to time constant of the intensifier. A faster time constant intensifier is desirable.

Defocused DIMM is good for only very bright stars due to low light levels and is less reliable than focused DIMM due to lower signal levels. Adding the image intensifier tends to help but again, frame rate is set by the time constant of the intensifier.

For all DIMM methods, lower frame rates lead to overestimation of r0. We advise that an observer must be careful as to choose the frame rate so that the instrument is not adding a bias to the r0 measurement. For most cases this would be frame rates greater than about 300.

9.2 Full Aperture Method

Full aperture method yields very good results for bright stars however this method also has some drawbacks. First, the method is very sensitive to image focus. The focusing of the star image becomes a crucial step in order to measure the true seeing conditions. Since focus is more or less qualitatively determined by the observer, a careful systematic approach must be practiced with rigid guideline for establishing the focused star image. It is also limited to plate scale of seeing monitor system. For our CCD, the plate scale is in the order of 0.66 arcsec per pixel which is the typical of CCD one can buy for less than about $5,000. The resolution of the star image relies heavily on this plate scale. To measure better seeing, CCD must be replaced with smaller pixels. However, smaller pixel also means less total area. As most observers know tracking is not perfect in any system hence the star tend to move out of the view quite often. Hence less total view area on the CCD can cause quite difficulties during observation. A good balance between the pixel size and the field of view is recommended.

Regarding the optimal frame rate for the full aperture method, we find that lower frame rates lead to underestimation of r0. The integration time is the crucial factor for obtaining the correct r0. As frame rate decreases, the star image is integrated more. This leads to bigger star image (bigger FWHM) hence yielding lower r0. We have experimented with several combinations of star magnitude and frame rate and find it true for all cases. We recommend higher than 300 frames/sec for correct r0 measurement.

Overall, we recommend that observer use both DIMM and the full aperture method to cross check and verify its results. Both methods are fairly easy to do out in the field and it ensures correct seeing measurement at the site. It provides an alternative measurement to allow for calibration of DIMM system.

10.0 References

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